CRIMINOLOGY

HEART RATE AND ANTISOCIAL BEHAVIOR: THE MEDIATING ROLE OF IMPULSIVE SENSATION SEEKING

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Although a low resting heart rate is considered the best-replicated biological correlate of antisocial behavior, the mechanism underlying this relationship remains largely unknown. Sensation-seeking and fearlessness theories have been proposed to explain this relationship, although little empirical research has been conducted to test these theories. This study addressed this limitation by examining the relationship between heart rate and antisocial behavior in a community sample of 335 adolescent boys. Heart rate was measured during a series of cognitive, stress, and rest tasks. Participants also completed self-report measures of state fear, impulsive sensation seeking, and both aggressive and nonaggressive forms of antisocial behavior. As expected, increased levels of aggression and nonviolent delinquency were associated with a low heart rate. Impulsive sensation seeking, but not fearlessness, significantly mediated the association between heart rate and aggression. This study is the first to show that impulsive sensation seeking partly underlies the relationship between aggression and heart rate, and it is one of the few to examine the mechanism of action linking heart rate to antisocial behavior. Findings at a theoretical level highlight the role of impulsive sensation seeking in understanding antisocial behavior and at an intervention level suggest it as a potential target for behavioral change.

Autonomic nervous system activity has long been examined in relation to psychopathy, aggression, and antisocial behavior (e.g., Davies and Maliphant, 1971; Hare, 1968). Psychophysiological indices of autonomic activity, which are noninvasive to record and capture nearly immediate physiological changes in response to external stimuli, include skin conductance, heart rate, and skin-potential response. Of these measures, a low resting heart rate is considered the best-replicated biological correlate of antisocial behavior in children and adolescents (Lorber, 2004; Ortiz and Raine, 2004). One meta-analysis

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of 45 independent effect sizes and a total of 5,868 children reported an effect size of $d = -.44$ ($p < .0001$) for the relationship between resting heart rate and antisocial behavior (Ortiz and Raine, 2004). In another meta-analysis, Lorber (2004) found an effect size of $d = -.38$ ($p < .05$) for studies of resting heart rate versus aggression. The relationship between low heart rate and antisocial behavior is unlikely to be the result of artifact; several key variables—including body size, intelligence, exercise, and socioeconomic status—have not been found to reduce the strength of this relationship substantially (Raine, 2002). Despite this well-documented association between a low heart rate and antisocial behavior, important gaps in our understanding of this relationship remain. These gaps include a limited understanding of the mechanism linking heart rate to antisocial behavior, as well as limitations in our understanding of the particular types of antisocial behavior that are associated with heart rate. The purpose of this article is to address these limitations.

MEDIATING MECHANISM

Perhaps surprisingly, given the large amount of research examining the heart rate–antisocial behavior relationship, the mechanism underlying this relationship remains largely unknown, although several theoretical explanations have been proposed. One theoretical explanation, sensation-seeking theory, rests on the premise that a low resting heart rate is a marker of low autonomic arousal (Raine, 2002). Low arousal is hypothesized to be an unpleasant physiological state, leading those with low resting heart rates to seek stimulating behaviors, including antisocial behaviors, to increase their level of physiological arousal to a more optimal level (Quay, 1965; Raine, 2002). Despite its status as a long-standing theory of antisocial behavior (Quay, 1965), the theory has been subjected to little empirical verification.

An alternative interpretation of the heart rate–antisocial behavior relationship, fearlessness theory, recognizes that the testing situation during which heart rate is measured may itself be at least mildly stressful. The "resting" states when heart rate is typically monitored—usually a 2- to 3-minute period prior to the beginning of a series of experimental tasks that are novel to the child in an unfamiliar laboratory setting—are likely to contain a modest element of anticipatory anxiety. Additionally, the measurement of heart rate often co-occurs with the administration of more stressful procedures, such as exposure to aversive stimuli or participation in a stressor task. A low heart rate, therefore, may indicate a relative lack of fear in response to moderate stressors (Raine, 1993; Venables, 1987). Fearlessness is thought to be related to antisocial behavior, as committing criminal and antisocial acts would be facilitated by a lack of fear regarding the antisocial context and potential punishment if apprehended (Raine, 2002). Additionally, poor fear conditioning and lack of anticipatory fear are well-replicated risk factors for antisocial behavior (Gao et al., 2010; van Goozen et al., 2004). These findings suggest that a relative lack of fear may underlie the heart rate–antisocial behavior relationship.

Most empirical support for the sensation-seeking and fearlessness theoretical interpretations has been indirect. For example, in one sample, fearlessness, stimulation seeking, and having a low resting heart rate at 3 years of age predicted aggression at 11 years of age (Raine et al., 1998; Raine, Venables, and Mednick, 1997). Recently, a novel study provided a more direct test of these explanations (Sijtsema et al., 2010). Resting heart rate was measured in a sample of males and females at age 11 years, and antisocial behavior was measured at age 16 years. Resting heart rate was not associated with antisocial behavior in females. In males, however, sensation seeking at 13.5 and 16 years of age, but not at 11 years of age, partially mediated the relationship between resting heart rate at 11 years of age and rule breaking at 16 years of age. Fearlessness, in contrast, did not mediate the relationship between heart rate and aggression.

Although this study was an important step toward improving our understanding of the heart rate–antisocial behavior relationship, some limitations preclude firm conclusions. First, the study tested fearlessness theory using measures of behavioral inhibition, effortful control, and impulsivity, rather than a more direct measure of fear. Although behavioral inhibition and impulsivity are closely related to fear, they are not identical constructs, leaving open the possibility that low fear may underlie the heart rate–antisocial behavior relationship. Another important limitation was that although the authors tested sensation seeking as a mediator of the heart rate–rule-breaking relationship, they did not test whether sensation seeking also mediated the relationship between heart rate and aggression. It remains unknown whether sensation seeking also partly underlies the heart rate–aggression relationship, leaving a critical gap in our understanding of this association. It also should be noted that Sijtsema et al. (2010) analyzed heart rate measured only during rest rather than including a more trait-like estimate of heart rate that could not be derived from the measurement of heart rate during rest alone.

BEHAVIORAL SPECIFICITY

Also, it is unknown whether the relationship between cardiac activity and antisocial behavior is specific to particular types of antisocial behavior. In a meta-analysis, Lorber (2004) found that resting heart rate was significantly ($p < .05$) associated with aggression ($d = -.38$) and conduct problems ($d = -.33$) but not with psychopathy ($d = .06$). However, Lorber's (2004) meta-analysis did not include any psychopathy studies with child or adolescent samples, leaving open the possibility that a low heart rate may be associated with psychopathy in youths. Consistent with this result, Baker et al. (2009) found that a low resting heart rate at 9–10 years of age predicted psychopathy at 9–10 years of age and 11–14 years of age in a community sample. To our knowledge, no other study has examined this effect in a study of heart rate measured during adolescence in a Western community sample, which leaves unresolved the question of whether a low heart rate characterizes adolescents with psychopathic-like characteristics.

CURRENT STUDY

The purpose of the current study is to address these limitations by determining whether heart rate measured during rest, cognitive challenge, and stress is associated with antisocial behavior. We hypothesize that a low heart rate will be associated with higher levels of antisocial behavior. We also hypothesize that the relationship between heart rate and antisocial behavior will be mediated by fearlessness and sensation seeking. Additionally, we predict that any indirect effects will remain significant after controlling for hypothesized confounders of the heart rate–antisocial behavior relationship.

METHODS

The data for this study come from the youngest of the three samples making up the Pittsburgh Youth Study. Full details of background characteristics and initial participant recruitment in 1987–1988 when children (all male) were 7 years of age are given in Loeber et al. (1998). Briefly, 868 first-grade boys from public schools in Pittsburgh, PA, were assessed by caretakers, teachers, and the boys themselves on 21 serious antisocial behaviors. The 250 most antisocial boys were selected for further study, together with 253 boys randomly selected from the remainder, to make a total sample of 503. As such, this population-based community sample, although representative of the children in public schools in the city of Pittsburgh, was weighted toward containing more antisocial boys so that sufficient numbers of such boys would be represented.

Of the original sample of 503 individuals, 335 individuals (66.6 percent) participated in a substudy on the biosocial bases of aggressive and violent behavior. The 10-year attrition of 168 individuals (33.4 percent) for the substudy broke down as follows: 31 participants lived out of the area, 20 were in jail, 45 refused the larger Pittsburgh Youth Study, 35 refused the biosocial study, 27 canceled appointments repeatedly, and 10 failed to decide on participation. Participants were compared with nonparticipants on initial data collected at 7 years of age to assess for bias. No evidence of selective attrition was found based on early data; participants did not differ significantly from nonparticipants on socioeconomic status (SES), ethnicity (Black vs. White), initial risk status, delinquency seriousness (no or minor delinquency vs. moderate or serious delinquency), or violence seriousness (no violence vs. gang fighting and attacks).

The 335 participants had a mean age of 16.15 years at the time of testing (standard deviation [SD] = 0.89). Overall, 41.2 percent of participants were Caucasian and 58.8 percent were African American. Full written informed consent was obtained from the boys and their parents, and study protocols were approved by the institutional review boards at both the University of Southern California and the University of Pittsburgh.

PSYCHOPHYSIOLOGICAL TESTING PROCEDURE

Heart rate was measured continuously during an initial resting period (3 minutes), a social stressor task (4 minutes), a cognitive task (8 minutes), and a final resting period (3 minutes). During the first rest, participants were seated and told that for the next few minutes, nothing would happen and they should sit still with their eyes closed. After a few minutes, the participants were told that they would hear some tones but that there was nothing they needed to do except to stay still. Subjects then completed a social stressor task (Raine et al., 2000). This task was video recorded to increase the level of stress experienced by subjects. Subjects were instructed to spend 2 minutes thinking about the worst or most stressful thing that had ever happened to them. After 2 minutes, they were told to describe the event to an experimenter for an additional 2 minutes. Only the heart rate measurements recorded during the first 2 minutes (the thinking period) of the stress task were analyzed in this study, as the act of speaking may interfere with the measurement of cardiovascular activity (Lynch et al., 1981).

Version 4.08 of the degraded stimulus version of the Continuous Performance Task (CPT; Nuechterlein, Parasuraman, and Jiang, 1983) was then administered according to the author's guidelines. Visually degraded numbers ranging from 0 to 9 were flashed on a computer screen (placed 1 m from the participant in his line of vision) for 40 ms at the rate of one per second. The participants' task was to press a response button on a Gravis joystick every time he saw the figure "0" but not to respond to all other stimuli. Targets had a 0.25 probability of occurrence. After 10 presentations of the target stimulus only, participants were given two practice blocks with 80 trials/block (for a total of 160 trials). Thereafter, six blocks with 80 trials in each block (for a total of 480 trials) were presented, lasting 8 minutes. After completing the CPT, subjects completed the final resting task. They were again told that for the next few minutes, nothing would happen and they should sit still with their eyes closed.

CARDIOVASCULAR RECORDING AND DATA REDUCTION

Heart rate was recorded using a Grass model 12 acquisition system (Grass Products, Warwick, RI). Sensor Medics Ag/AgCl electrodes (Sensor Medics Corp., Homestead, FL) were placed below the right collarbone and below the left lower rib using Medi-Trace conductivity gel (Covidien, Mansfield, MA). Respiration rate was measured using a strain gage placed around the chest in conjunction with a strain gage bridge transducer coupler, and it was sampled at 5 Hz. The electrocardiography signal was digitized at 256 Hz and stored for offline processing sequence.

The time between successive R-waves was stored and input together with respiration rate into the PSPAT software program, which conducted artifact correction, performed spectral analysis of the cardiac data, and corrected for any nonstationarity in the data (Weber, Molenaar, and van der Molen, 1992). The heart rate levels were calculated by averaging interbeat intervals throughout each task and converting values to beats per minute.

AGGRESSION MEASURES

Reactive and Proactive Aggression

Both reactive and proactive aggression were measured using the reactive and proactive subscales of the Reactive-Proactive Questionnaire (RPQ; Raine et al., 2006). The RPQ is a self-report instrument with 12 proactive items (e.g., “Had fights with others to show who was on top”) and 11 reactive items (e.g., “Reacted angrily when provoked by others”). Respondents rated how often they had engaged in the items on a three-point scale (0 = never, 1 = sometimes, and 2 = often). The scores on each subscale were summed to create total reactive aggression and total proactive aggression scores. The RPQ has been shown to be a valid and reliable assessment of reactive and proactive aggression in this sample (Raine et al., 2006), as well as in other samples (Baker et al., 2008; Fossati et al., 2009; Fung, Raine, and Gao, 2009). Outliers greater than 3 standard deviations away from the mean for each scale were coded as missing (Tabachnick and Fidell, 2013), resulting in the exclusion of two cases for the reactive aggression scale and four cases for the proactive aggression scale.

Violent Delinquency

Subjects were administered the Self-Reported Delinquency Scale (SRD; described in more detail in Stouthamer-Loeber and Stallings, 2008). Subjects indicated the number of times in the past year they had committed a series of violent and nonviolent delinquent acts. The definition of violence adopted by the National Academy of Sciences Panel on the Understanding and Control of Violent Behavior (“behaviors by individuals that intentionally threaten, attempt, or inflict physical harm on others,” Reiss and Roth, 1993: 2) was used to classify behaviors as violent. Six items met this criterion (e.g., “How many times in the past year have you hit someone with the idea of hurting them”). Because there was a high skew toward zero on most of the items, dimensional frequency scores were not appropriate. Instead, subjects were given a score of 1 if they had committed the violent behavior and a score of 0 if they had not committed the behavior. The scores for each of the six included items were summed to create a total violent delinquency score. This type of variety scoring has been shown to have advantages over frequency scoring in terms of reliability and construct validity (Bendixen, Endresen, and Olweus, 2003). The internal reliability (Cronbach's alpha) for the scale was .61 in this sample.

PSYCHOPATHY

The Child Psychopathy Scale (CPS; Lynam, 1997) was completed by the boys. The instrument was designed to operationalize, in childhood and adolescence, the traits found in the Psychopathy Checklist-Revised (Hare, 1991). The instrument is well validated in this population (Falkenbach, Poythress, and Heide, 2003; Lynam, 1997), and the internal reliability (Cronbach's alpha) of the scale in this sample is .92 (Raine et al., 2006).

NONVIOLENT DELINQUENCY

Seventeen items from the SRD instrument were used to create a nonviolent delinquency scale (e.g., "How many times in the past year have you purposely damaged or destroyed property that did not belong to you"). Subjects were given a score of 1 if they had committed the nonviolent act and a score of 0 if they had not committed the behavior. These scores were summed to create a total nonviolent delinquency score. The internal reliability (Cronbach's alpha) for the index was .71 in this sample.

IMPULSIVE SENSATION SEEKING

Impulsive sensation seeking was assessed using the impulsive sensation-seeking subscale of the Zuckerman-Kuhlman Personality Questionnaire (ZKPQ; Zuckerman et al., 1993). The impulsive sensation-seeking scale contains 19 items that assess a lack of planning, impulsive behavior, and the tendency to take risks in the pursuit of excitement or novelty (e.g., "I like doing things just for the thrill of it"). Items were coded as 1 if the subject indicates the item is true and 0 if the item is false. Higher scores indicate a higher level of impulsive sensation seeking. The impulsive sensation-seeking scale has been shown to be reliable and valid (Zuckerman and Kuhlman, 2000; Zuckerman et al., 1993), and it has a Cronbach's alpha of .73 in this sample.

STATE FEAR

Subjects completed the Positive and Negative Affect Schedule (PANAS; Watson, Clark, and Tellegen, 1988) five times throughout the experimental session. Subjects were shown 20 words that describe feelings and emotions, and then they indicated the extent to which they felt that way at that moment on a five-point Likert scale. For each item, we calculated each participant's average score across the five administrations of the PANAS. Although the PANAS was originally designed to measure two dimensions of affect—positive and negative (Watson, Clark, and Tellegen, 1988)—more recent psychometric research revealed that a three-factor solution that includes an Afraid factor may be a better fit for the items on the PANAS (Gaudreau, Sanchez, and Blondin, 2006; Killgore, 2000; Mehrabian, 1997). Therefore, we subjected the 20 average item scores to a principal factor analysis with an Oblimin rotation (delta = .2) using SPSS statistical software (IBM SPSS Statistics Version 20.0; SPSS Corporation, Chicago, IL). Four factors had eigenvalues > 1. However, a four-factor solution failed to satisfy the constraints of Cattell's scree test. Therefore, only three factors were retained. Factor 1 consisted of 10 Positive Affect items (e.g., interested and excited) with factor loadings between .48 and .84 (Cronbach's alpha = .91). Factor 2 consisted of 7 Negative Affect items (e.g., distressed and upset) with factor loadings between .42 and .80 (Cronbach's alpha = .80). The "scared," "nervous," and "afraid" items loaded onto Factor 3, with factor loadings of –.90, –.53, and –.95, respectively.

Because of the a priori focus on fearlessness, only items on the third factor were used in our analyses. The scores for these three items were summed to create an index of fearfulness during the testing session, with higher scores indicating increased state fearfulness. Nine outliers with scores greater than three standard deviations from the mean were coded as missing. The internal reliability (Cronbach's alpha) for the third factor was .79. All correlations among the nervous, afraid, and scared items were significant and ranged from .55 to .84.

COVARIATES

Body mass index (BMI), race, socioeconomic status (SES), maternal teenage pregnancy, and physical activity were examined as possible confounders of the heart rate–antisocial behavior relationships. BMI was derived from height measured using a stadiometer attached to the wall, and weight was measured using digital scales. BMI was calculated as kilograms/m^2. Race was coded as 0 for African American or 1 for Caucasian (Stouthamer-Loeber and Stallings, 2008). SES was used as an indicator of early social adversity. SES was measured during the boys' age 7 assessments using the Hollingshead (1975) index, which is based on parental occupational prestige and education level. Additional details on the measure can be found in Loeber et al. (1998). Maternal teenage pregnancy was used as an additional indicator of early psychosocial adversity. Mothers reported their age at the birth of the boy during the age 7 assessment. Mothers 20 years of age or older at the birth of the boy were given a score of 0. Teenage mothers (mothers that were less than 20 years of age at the birth of the boy) were given a score of 1. To develop a measure of physical activity, subjects were asked how many times in the past month they had participated in a series of physical activities (e.g., jogging, football, and other) for at least 30 minutes. The totals for each activity were summed to create a physical activity score, with two scores greater than three standard deviations from the mean coded as missing. Self-reported physical activity questionnaires have been shown to be reliable and valid among adolescents (Sallis et al., 1993).

STATISTICAL ANALYSES

Bivariate correlations among the observed study variables were performed using SPSS statistical software (IBM SPSS Statistics Version 20.0). Structural equation models were estimated in Mplus Version 7 to test impulsive sensation seeking and state fear as mediators of the heart rate–aggression and heart rate–nonviolent delinquency relationships. Parameter estimates were calculated using maximum likelihood with robust standard errors to account for non-normality in the data. To test the significance of the indirect effects, bias-corrected confidence intervals (CIs) for the indirect effects were generated

Table 1. Bivariate Correlations Among Observed Study Variables

Variable	1	2	3	4	5	6	7	8	9	10	11
Heart Rate											
1. Heart rate rest 1	1.00										
2. Heart rate CPT	.82**	1.00									
3. Heart rate stress	.91**	.83**	1.00								
4. Heart rate rest 2	.81**	.90**	.81**	1.00							
Antisocial Behavior											
5. Reactive	−.12*	−.15**	−.14*	−.16**	1.00						
6. Proactive	−.11	−.11	−.11*	−.13*	.62**	1.00					
7. Violent	−.08	−.12*	−.13*	−.15**	.37**	.50**	1.00				
8. Nonviolent	−.13*	−.13*	−.13*	−.13*	.37**	.45**	.62**	1.00			
9. Psychopathy	−.07	−.04	−.08	−.07	.49**	.50**	.25**	.37**	1.00		
Potential Mediators											
10. Impulsive sensation seeking	−.09	−.10	−.09	−.10	.30**	.23**	.25**	.25**	.43**	1.00	
11. Fear	−.03	−.02	.03	−.01	.15**	.06	−.01	.01	.12*	.10	1.00
Mean	68.28	68.21	67.97	65.96	7.05	2.62	.48	.71	4.21	9.75	3.68
SD	10.24	10.06	10.06	10.13	4.06	3.14	.92	1.42	2.01	3.67	.79

NOTE: $N = 301$–335.
ABBREVIATIONS: Fear = Positive and Negative Affect Schedule state fear score; Heart rate CPT = heart rate during the Continuous Performance Task; Heart rate rest 1 = heart rate during first rest; Heart rate rest 2 = heart rate during the final rest; Heart rate stress = heart rate during stressor; Impulsive sensation seeking = score on the impulsive sensation seeking scale of the Zuckerman-Kuhlman Personality Questionnaire; Nonviolent = nonviolent delinquency; Proactive = proactive aggression; Reactive = reactive aggression; SD = standard deviation; Violent = violent delinquency.
$^{*}p < .05$; $^{**}p < .01$.

using 1,000 bootstrap samples. A bootstrap approach was used, as opposed to the more traditional Sobel test, because the bootstrap method has higher statistical power and makes more realistic assumptions about the sampling distribution of the indirect effect (MacKinnon, Lockwood, and Williams, 2004).

The percentage of missing data for the observed study variables ranged from 0 percent for the violent and nonviolent delinquency scores to 6.6 percent for heart rate measured during the CPT. Missing data were handled using full-information maximum likelihood procedures, which often provide more efficient parameter estimates than other approaches to handling missing data (Olinsky, Chen, and Harlow, 2003).

RESULTS

BIVARIATE ASSOCIATIONS

Bivariate correlations among the observed variables are shown in table 1. A low heart rate was associated with higher levels of reactive aggression, proactive aggression, violent delinquency, and nonviolent delinquency ($p < .05$ for most relationships), although heart rate was not associated with psychopathy ($p > .05$). Increased impulsive sensation seeking was associated with higher levels of the antisocial behavior measures ($p < .05$). State fear was not significantly associated with heart rate ($p > .05$), and contrary to expectations, high state fear was associated with increased reactive aggression and psychopathy scores ($p < .05$). Because physical activity and race were the only hypothesized confounds to

Table 2. Bivariate Correlations Among Observed Study Variables and Covariates

Variable	Physical Activity	SES	Teen Mom	BMI	Race
Heart rate rest 1	−.22*	.08	−.06	.04	.22**
Heart rate CPT	−.25**	.09	−.06	−.02	.21**
Heart rate stress	−.24**	.11	−.06	.06	.30**
Heart rate rest 2	−.25**	.09	−.06	.02	.22**
Reactive	.16**	−.06	.02	−.07	−.05
Proactive	.15**	−.16**	.11	−.08	−.13*
Violent	.19**	−.04	.02	−.05	−.08
Nonviolent	−.08	−.08	.05	−.05	.01
Psychopathy	−.01	−.06	.03	.00	−.02
Impulsive sensation seeking	.09	−.01	−.02	−.05	.20**
Fear	.01	.06	.01	−.05	.13*
Mean	47.84	35.31	.21	23.45	.41
SD	32.58	13.40	.41	5.19	.49

NOTE: $N = 301$–335.

ABBREVIATIONS: BMI = body mass index; Fear = Positive and Negative Affect Schedule state fear score; Heart rate CPT = heart rate during the Continuous Performance Task; Heart rate rest 1 = heart rate during first rest; Heart rate rest 2 = heart rate during the final rest; Heart rate stress = heart rate during stressor; Impulsive sensation seeking = score on the impulsive sensation seeking scale of the Zuckerman-Kuhlman Personality Questionnaire; Nonviolent = nonviolent delinquency; Physical activity = number of times participated in physical activity during past month; Proactive = proactive aggression; Race = 0 if African American; Reactive = reactive aggression; SES = socioeconomic status; Teenage mom = 1 if mother was younger than age 20 years when boy was born; Violent = violent delinquency.

$^{*}p < .05$; $^{**}p < .01$.

be associated with heart rate and at least one antisocial behavior measure ($p < .05$; see table 2), only these variables were included as covariates in the mediation analyses.

MEASUREMENT MODELS

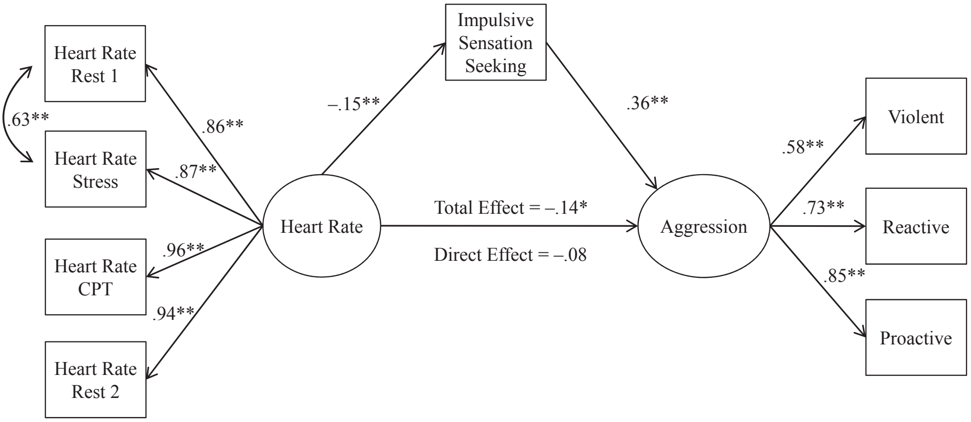
Given the high intercorrelations among the heart rate measures ($r = .81$ to .91), the four observed heart rate measures were used to create a latent variable representing trait heart rate. Because subjects may have experienced an increased stress level during the first resting period because of the novelty of the experimental situation, including the application of electrodes, the errors of heart rate measured during the first rest and heart rate during stress were freely correlated. The model provided an excellent fit for the data (root mean square error of approximation [RMSEA] = .000 with a 90 percent CI of .000 to .10; comparative fit index [CFI] = 1.00; standardized root mean square residual [SMSR] = .001). All standardized factor loadings were statistically significant ($p < .001$) and ranged from .86 to .96.

A latent variable was created to represent aggression using the violent delinquency, proactive aggression, and reactive aggression scores. Because there were only three indicators, the model fit could not be evaluated, although all standardized factor loadings were statistically significant ($p < .001$) and ranged from .68 to .92.

STRUCTURAL MODELS

As shown in figure 1, we first tested impulsive sensation seeking as a mediator of the heart rate–aggression relationship (with physical activity and race included as covariates).

Figure 1. Mediation Model Predicting Aggression



NOTE: The rectangles denote observed variables, and the circles denote latent variables. Standardized parameter estimates are shown. Curved lines represent correlations between variables' error terms. For ease of presentation, physical activity and race are not shown, although they were included as covariates in the model. N = 335.

ABBREVIATIONS: Heart rate CPT = heart rate during the Continuous Performance Task; Heart rate rest 1 = heart rate during first rest; Heart rate rest 2 = heart rate during the final rest; Heart rate stress = heart rate during stressor; Impulsive sensation seeking = score on the impulsive sensation seeking scale of the Zuckerman-Kuhlman Personality Questionnaire; Proactive = proactive aggression; Reactive = reactive aggression; Heart rate CPT = heart rate during the Continuous Performance Task, Heart rate rest 2 = heart rate during the final rest; Violent = violent delinquency; Reactive = reactive aggression; Proactive = proactive aggression; Impulsive sensation seeking = score on the impulsive sensation seeking scale of the Zuckerman-Kuhlman Personality Questionnaire.

$^{*}p < .05$; $^{**}p < .001$.

This model provided an excellent fit for the data (RMSEA = .04 with a 90 percent CI of .02 to .07; CFI = .99; SRMR = .02). As expected, impulsive sensation seeking significantly mediated the association between heart rate and aggression (indirect effect: $\beta = -.05$, $p < .05$), and it rendered the direct effect of heart rate on aggression nonsignificant ($\beta = -.08$, $p > .10$). The mediated effect explained 35.71 percent of the total effect of heart rate on aggression. The next mediation model (shown in figure 2) tested impulsive sensation seeking as a mediator of the heart rate–nonviolent delinquency relationship (with physical activity and race included as covariates). This model also provided an excellent fit for the data (RMSEA = .03 with a 90 percent C.I. of .000 to .07; CFI = .997, SRMR = .01). Impulsive sensation seeking significantly mediated the association between heart rate and nonviolent delinquency (indirect effect: $\beta = -.04$, $p < .05$). The mediated effect explained 26.67 percent of the total effect of heart rate on nonviolent delinquency, although the direct effect of heart rate on nonviolent delinquency remained significant ($\beta = -.11$, $p < .05$).

We then conducted analyses examining fear as a mediator of the heart rate–aggression and heart rate–nonviolent delinquency relationships. Contrary to expectation, the indirect effects in these models were not statistically significant ($p > .1$).[1]

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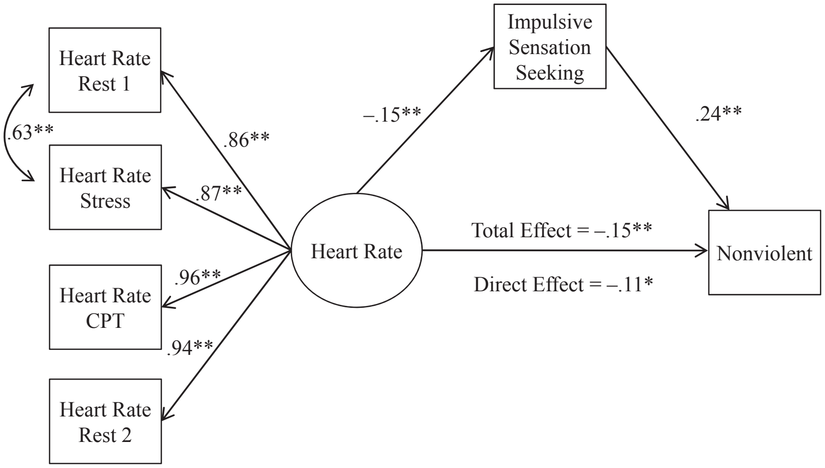
[1] To confirm that the null findings were not the result of problems with the measurement of fear, we repeated these analyses using a measure of state anxiety (Spielberger, Gorusch, and Lushene,

Figure 2. Mediation Model Predicting Nonviolent Delinquency



NOTE: The rectangles denote observed variables, and the circles denote latent variables. Standardized parameter estimates are shown. Curved lines represent correlations between variables' error terms. For ease of presentation, physical activity and race are not shown, although they were included as covariates in the model. N = 335.
ABBREVIATIONS: Heart rate CPT = heart rate during the Continuous Performance Task; Heart rate rest 1 = heart rate during first rest; Heart rate rest 2 = heart rate during the final rest; Heart rate stress = heart rate during stressor; Impulsive sensation seeking = score on the impulsive sensation seeking scale of the Zuckerman-Kuhlman Personality Questionnaire; Nonviolent = nonviolent delinquency.
$^{*}p < .05$; $^{**}p < .001$.

DISCUSSION

The objective of this study was to address important gaps in the literature by investigating the mechanism underlying the heart rate–antisocial behavior relationship and by examining heart rate in relation to multiple types of antisocial behavior. We found that a low heart rate was associated with higher levels of aggression and nonviolent delinquency and that impulsive sensation seeking mediated the relationship between heart rate and both aggression and nonviolent delinquency. This study is the first to show that impulsive sensation seeking mediates the relationship between heart rate and aggression and is one of a few studies to explore the previously unknown mechanism of action linking heart rate to antisocial behavior. Our findings provide support for an impulsive sensation-seeking model of antisocial behavior (Zuckerman, 2007) and provide further support for heart rate as a putative biomarker for conduct disorder (Moffitt et al., 2008).

MEDIATION

Our findings contribute to a growing body of indirect research suggesting sensation seeking as a mediator of the heart rate–antisocial behavior relationship. This research

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1970), parent-reported scores on the Anxious/Depressed scale of the Child Behavior Checklist (Achenbach and Edelbrock, 1983), and a latent fear variable based on the observed PANAS fear measures. All results were substantively unchanged, with the indirect effects remaining nonsignificant in each mediation model tested.

includes a meta-analysis of 40 studies, 43 independent effect sizes, and a total of 32,217 participants that found sensation seeking to be positively related to aggression (Wilson and Scarpa, 2011). Resting heart rate at 3 years of age also has been found to characterize both sensation-seeking behavior at 3 years of age and aggressive behavior at 11 years of age (Raine et al., 1998; Raine, Venables, and Mednick, 1997). Together, these findings support the possibility that some individuals with low heart rates engage in criminal and aggressive behavior as a form of sensation-seeking behavior to increase their optimal levels of arousal.

This sensation-seeking model of antisocial behavior is potentially consistent with other criminological theories of antisocial behavior. Gottfredson and Hirschi (1990) argued in their general theory of crime that individuals low in self-control tend to be adventuresome and risk taking—in addition to displaying more typical impulsive-like traits such as the inability to delay gratification—and that low self-control is the underlying cause of criminal behavior. Impulsive sensation seeking, therefore, seems to play a role in their conceptualization of self-control.

Other researchers also have identified a close link between impulsivity and sensation seeking (Zuckerman, 1993). Although some results have varied (Whiteside and Lynam, 2001), psychometric research in the domain of personality has found that impulsivity and sensation-seeking items load onto a single factor (Zuckerman et al., 1993), suggesting a close empirical link between the two traits. In addition, like sensation seeking, impulsivity is thought to be associated with reduced physiological arousal (Eysenck, 1993; Mathias and Stanford, 2003). At least two studies, however, found that the relationship between heart rate and antisocial behavior remained significant after controlling for a measure of self-control (Armstrong et al., 2009; Cauffman, Steinberg, and Piquero, 2005). It is possible, therefore, that the combined trait of impulsive sensation seeking, rather than impulsivity alone, best explains the heart rate–antisocial behavior relationship, although this possibility requires further investigation.

Like Sijtsema et al. (2010), we found that fearlessness did not underlie the heart rate–antisocial behavior relationship. The current finding advances this new knowledge by including a more direct measure of state fear during the testing session, as well as including a more robust measure of aggression and examining a more stable, trait-like estimate of heart rate. Fearlessness did not mediate the relationship between low heart rate and antisocial behavior for several possible reasons. First, it is important to note that high levels of antisocial behavior and heightened anxiety often are comorbid (Marmorstein, 2007; Sareen et al., 2004). Although anxiety and fear are not identical constructs, they are moderately correlated (Sylvers, Lilienfeld, and LaPrairie, 2011), suggesting that antisocial adolescents may not actually display increased anxiety and fearfulness on a day-to-day basis compared with their prosocial peers.

Our null finding has several possible explanations. Fearlessness has been hypothesized to explain the low heart rate–antisocial behavior relationship in part because a lack of fear of socializing punishments in childhood could impair fear conditioning and, in turn, disrupt conscience development (Raine, 2002). Therefore, it may be the case that heart rate is linked to antisocial behavior through its putative effects on conscious development. In preliminary support of this possibility, Armstrong and Boutwell (2012) found that the relationship between low heart rate and the intent to commit assault in a vignette scenario was mediated by the respondent's perceived likelihood of experiencing guilt or shame should he commit the act described in the vignette. Future research that examines heart rate in the context of both fear conditioning and conscious development may provide a useful next step in testing the fearlessness explanation of the heart rate–antisocial behavior relationship.

HEART RATE AND PSYCHOPATHY

We found that a low heart rate was associated with increased aggression and nonviolent delinquency, but as in prior studies (Lorber, 2004), psychopathy was not associated with heart rate. This study extended our current understanding by documenting a null finding in an adolescent, community sample. Although psychopaths grow up to be among the most violent and prolific offenders (Porter and Woodworth, 2006), our results show that, at least during adolescence, the etiology of their aggression differs from that of their nonpsychopathic peers. Prior research has shown that youth with callous-unemotional traits, which are key features of psychopathy, display distinct emotional, cognitive, and personality characteristics compared with other antisocial youth (Frick and White, 2008). Our results suggest that differences in autonomic nervous system functioning in psychopathic youth likely exists as well. It should be cautioned, however, that a recent study using a sample of East Asian youth between 11 and 17 years of age found that a low heart rate was significantly associated with overall levels of psychopathic traits (Raine et al., 2014). It is possible that comorbidity with aggressive behavior was driving the observed relationship with psychopathy, but until this speculation is confirmed, we caution against firm conclusions regarding the psychopathy–heart rate relationship in adolescents.

LIMITATIONS

The results from this study should be interpreted in light of some limitations. One limitation of the current study was that all measures were concurrent, which did not allow us to confirm the temporal ordering of the variables in the mediation model. It should be noted, however, that a low heart rate predicts antisocial behavior in prospective longitudinal research (Farrington, 1997; Jennings, Piquero, and Farrington, 2013; Raine, Venables, and Mednick, 1997; Sijtsema et al., 2010) and that sensation seeking predicts aggression at later ages (Raine et al., 1998). Therefore, a strong theoretical basis exists for assuming the correct temporal ordering of the variables.

Limitations also included the fact that the sample in this study included only boys. It is possible that our findings may not generalize to females, with a recent study documenting inconsistent relationships between sensation seeking and heart rate in females (Wilson and Scarpa, 2013). In contrast, gender was not found to moderate significantly the effect size in a meta-analysis of resting heart rate versus antisocial behavior (Ortiz and Raine, 2004), providing suggestive evidence that our findings also may generalize to females. Additionally, although this was a community sample that was representative of the children in public schools in Pittsburgh, the sample was weighted toward having more antisocial boys. Thus, this sample was not fully representative of American adolescents. Nonetheless, it should be noted that heart rate has been associated with antisocial behavior in both high-risk (e.g., Lösel and Bender, 1997) and community samples (e.g., Armstrong et al., 2009; Raine, Venables, and Mednick, 1997), thus, increasing the possibility that these results could generalize to other groups.

Other theoretical explanations of the heart rate–antisocial behavior relationship could not be tested in the current study. Raine (2002), for instance, suggested that reduced functioning in the right hemisphere of the brain could underlie both low resting heart rate and antisocial behavior. In support of this possibility, the right hemisphere is dominant for the modulation of sympathetic cardiac functioning (Nagai, Hoshide, and Kario, 2010; Yoon et al., 1997), and its reduced functioning is associated with reduced cardiac activity (Barron, Rogovski, and Hemli, 1994). Structural and functional abnormalities in the right hemisphere of the brain also have been linked to antisocial behavior (Narayan et al., 2007; Raine et al., 2002, 2005). Given that resting heart rate and antisocial behavior are both partly heritable (Hanson et al., 1989; Rhee and Waldman, 2002), another possibility is that the same genes encode for both heart rate and processes that predispose to antisocial behavior (Baker et al., 2009; Ortiz and Raine, 2004). Each of these explanations, although theoretically justified, requires further investigation.

CONTRIBUTIONS AND FUTURE DIRECTIONS

The preceding limitations should be viewed in the context of several strengths to this study. Importantly, the current findings advance our understanding of the mechanism underlying the heart rate–aggression relationship by showing for the first time that impulsive sensation seeking mediated this association. Additionally, although it is argued that a low heart rate is diagnostically specific to conduct disorder (Ortiz and Raine, 2004—heart rate is not known to be associated with any other psychiatric condition, including alcoholism or schizophrenia), we took this research a step further by demonstrating that a low heart rate may be associated only with nonpsychopathic forms of antisocial behavior in adolescents.

We also showed that the heart rate–aggression relationship was robust, given that heart rate was associated with a measure of violent delinquency, as well as with reactive and proactive aggression. These relationships were present when a more stable, trait-like measure of heart rate was employed that captured heart rate activity across several conditions, including during rest, during cognitive challenge, and during an emotional challenge. These robust results provide added support for the claim that a low heart rate may potentially serve as a putative biomarker for conduct disorder (Moffitt et al., 2008).

The results of this study point to the need for additional research that seeks alternative mechanisms that may contribute to the heart rate–nonviolent delinquency relationship. The results of this and other research could have important implications for treating antisocial behavior. Stadler et al. (2008), for instance, showed that a behavioral intervention for children with disruptive behavior disorders was less effective for children with low baseline heart rates. These findings indicate that children with low heart rates may require specialized interventions. In light of our own findings, interventions for children with low autonomic arousal may be most effective when aimed at encouraging children to participate in prosocial, stimulating behaviors that can partly fulfill their need for stimulation. Examining low heart rate in the context of behavioral interventions could provide a promising avenue for future research efforts that could be bolstered by future investigations into mediating mechanisms.

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